REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
July 20, 1995

3. REPORT TYPE AND DATES COVERED
Summary 15 June 94 to 31 May 1995

4. TITLE AND SUBTITLE
Tunneling Acoustic Microscopy

5. FUNDING NUMBERS
PE 61153N
G N00014-94-1-0730
TA 3126980

6. AUTHOR(S)
B. T. Khuri-Yakub

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
E. L. Ginzton Laboratory
Stanford University
Stanford, CA 94305-4085

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
ONR 331
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Silicon micro machining has been used to make novel ultrasonic air transducers. A model describing the behavior of capacitive membranes under the application of dc and ac bias has been developed. Transmission experiments in air have been made at frequencies of up to 11.5 MHz. Different criteria have been devised for efficient transmitters (up to 5000Å displacement in air) and for sensitive receivers (displacements as small as 0.001Å are detected in a 2 MHz bandwidth and with 20 dB signal to noise ratio). These devices have applications in ranging, non destructive evaluation, gas flow and composition, and most importantly as hydrophones in underwater applications. Another novel application for this technology and devices is as arrays, in two dimensions, for atomic force microscope and tunneling microscopes probe displacement sensors. In this embodiment, arrays of atomic tips are actuated and their displacement sensed for applications in imaging and lithography.

14. SUBJECT TERMS
Silicon micro machining, capacitive transducers, hydrophones non destructive evaluation, in-situ process sensors, acoustic, arrays, scanning probes

15. NUMBER OF PAGES
19

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified	unclassified	

36K

NSN 7540-01-280-5500

Standard Form 298 (Rev 2 89)
Prescribed by ANSI Std Z39-18

ANNUAL SUMMARY REPORT

JUNE 15, 1994 TO MAY 31, 1995

A. Description of Project

The objectives of this research are to develop ultrasonic sensors and actuators using silicon micro machining, and to develop theoretical models of the behavior of these devices. A number of applications are envisaged in the fields of in-situ sensors, ranging, hydrophones, sensors for scanning atomic tips in imaging and lithography, and non destructive evaluation.

B. Approaches taken

The ability to control dimensions in semiconductor materials using micro machining techniques opens the way for a large number of ultrasonic sensors and actuators that are not amenable by conventional technologies. We use this technology to make capacitive ultrasonic transducers with gaps in the 1 μm range and resonant frequencies in the 0.5 MHz to 25 MHz range. The fractional bandwidth of these devices ranges from 2% to 20 % depending on the final shape of the resonant membranes. In water immersion applications, the fractional bandwidth ranges over several orders of magnitude.

Simple thin film deposition, thin film etching (wet and dry), and standard photolithography are used to make capacitive transducers with thin membranes (<1μm), thin gap (around 1 μm), residual stress levels around 300 MPa, and with a resonant frequency in the 0.5 MHz to 25 MHz range. The devices behave as thin membranes whose behavior is dominated by the residual stress, and dimensions of the membrane.

Theoretical models have been developed to predict both the dc and ac behavior of these devices while operating into air or water. Processes have been developed to make devices for operation in air and water. An optical interferometer is used to measure the

displacement of the membrane for comparison with theory, and electronic set ups are made to test the devices' input impedance and insertion losses.

C. Accomplishments

A model describing the behavior of the membranes under DC bias has been developed. We find that it is possible to apply enough DC voltage to collapse the membrane into the back electrode. Hysterisis is a feature of the DC operation as it takes a lower voltage to maintain the membrane in contact with the back electrode. We find that the maximum ac displacement of a membrane, peak to peak, is about 30% of the total gap height. For instance, in a 1 μm gap, the maximum peak to peak displacement is 3000 Å. However, it is possible to operate devices in and out of collapse and generate large ultrasonic power in air. Such a mode of operation could be desirable, for instance, for modifying, by streaming, the boundary layer over the wings of airplanes.

An AC model has been developed to predict the behavior of the membranes as transmitters and receivers. As a transmitter, it is possible to generate more power in air than with piezoelectric which get into saturation and nonlinear behavior at the level of strains corresponding to 3000 Å level of displacement. Our model, along with some sensitive electronics indicate that we can detect 0.001 Å displacement with a bandwidth of 2 MHz and a signal to noise ratio of 20 dB. Optimizing the gap height, and reducing the bandwidth will allow us to detect displacements as small as 10^{-6} Å. Thus, even as receivers, it is possible to make the capacitive micro machined air transducers more sensitive than their piezoelectric counterparts. The bandwidth predicted for these devices is of the order of 3% when each circular membrane is fully supported at the periphery. However, experiments with membranes that are supported on posts show fractional bandwidth of the order of 20%. Our plan for the following year is to develop the models necessary to predict the resonant behavior of membranes that are supported on posts of different dimensions.

A number of devices were made and operated at frequencies of up to 11.5 MHz. This is the first report of such high frequency transmission of ultrasound in air over distances of the order of a few millimeters. We encountered some problems with the metal films on the transducers, but we expect the next generation of devices to take care of this problem, and make a large number of applications a reality. A paper is being prepared for submission to Applied Physics Letters on the subject.

A couple of new applications are now in consideration for these devices. One, which is the subject of a patent disclosure under preparation, is to place atomic tips on the membranes and use the capacitive transducers as sensors of force, and actuators for tip positioning. This is probably the only viable method for making 2-Dimensional arrays of atomic tips for imaging and lithography applications. The next application we plan to investigate in the next reporting period, is to develop water immersion version of the devices for use as hydrophones. The interest in this area is for Navy applications in underwater detection and for medical ultrasound.

OFFICE OF NAVAL RESEARCH

PUBLICATION/PATENTS/PRESENTATION/HONORS REPORT

for

15 June 94 through 30 June 95

R&T Number: 3126980---01

Contract/Grant Number: N00014-94-1-0730

Contract/Grant Title: Tunneling Acoustic Microscopy

Principal Investigator: Butrus T. Khuri-Yakub

Mailing Address: E. L. Ginzton Lab. rm. 11
Stanford University
Stanford, CA 94305-4085

Phone Number (With Area Code): (415) 723-0718 Fax: (415) 725-7509

E-Mail Address: khuri-ya@ee.stanford.edu

a. Number of Papers Submitted to Referred Journal but not yet published: 1 (in preparation)

b. Number of Papers Published in Referred Journals: 0

c. Number of Books or Chapters Submitted but not yet Published: 1 (in preparation)

d. Number of Books or Chapters Published: 0

e. Number of Printed Technical Report & Non-Referred Papers: 2 (in preparation)

f. Number of Patents Filed : 1 (in preparation)

g. Number of Patents Granted: 0

h. Number of Invited Presentations at Workshops or Prof. Society Meetings: 1

i. Number of Presentation at Workshop of Prof. Society Meetings: 0

j. Honors/Awards/Prized for Contract/Grant Employees: Prof. Khuri-Yakub Elected Fellow of the IEEE

k. Total number of Graduate Students and Post-Docs Supported at least 25%, this year of this contract, grant:

Grad student 1 and Post Docs 0

MICROMACHINED ULTRASONIC TRANSDUCERS (MUTs): 11.4 MHz TRANSMISSION IN AIR AND MORE

Igal Ladabaum, B.T. Khuri-Yakub
E. L. Ginzton Laboratory, Stanford University, Stanford, CA 94305

Dimitri Spoliansky
Ecole Normale Supérieure, 45 Rue D'Ulm, 75005 Paris, FRANCE

ABSTRACT

The successful fabrication and modeling of novel, capacitive, ultrasonic air transducers is reported. Transmission experiments in air at 11.4 MHz, 9.2 MHz, and 3.1 MHz are shown to correspond with theory. The transducers are made using surface micromachining techniques, which enable the realization of center frequencies ranging from 1.8 MHz to 11.6 MHz. The bandwidth of the transducers ranges from 5% to 20%, depending on processing parameters. Custom circuitry is able to detect 10 MHz capacitance fluctuations as small as 10^{-18} F, which correspond to displacements on the order of 10^{-3} Å (with potential for 10^{-5} Å), in a bandwidth of 2 MHz with a signal to noise ratio of 20 dB. Such detection sensitivity is shown to yield air transducer systems capable of withstanding over 100 dB of signal attenuation, a figure of merit that has significant implications for ultrasonic imaging, nondestructive evaluation, gas flow and composition measurements, and range sensing.

Micromachining is the chosen vehicle for device fabrication because the membrane's dimensions (microns) and residual stress (hundreds of MPa's) can be tailored to yield mechanical resonance frequencies in the MHz range. Silicon and silicon nitride have excellent mechanical properties, and can be readily patterned using the wide repertoire of procedures invented by the semiconductor industry.

The fabrication sequence is remarkably simple (Figure 2). A highly doped, p-type <100> 4" silicon wafer is cleaned and a 1μm oxide layer is grown with a wet oxidation process. A 5000 Å layer of LPCVD nitride is then deposited. The residual stress of the nitride can be varied by changing the proportion of silane to ammonia during the deposition process. After the backside of the wafer is stripped, a chrome adhesion layer and a 500 Å film of gold are evaporated onto both sides of the wafer. A pattern of etchant holes is then transferred to the wafer lithographically, followed by a gold and nitride etch. Thus, access holes are generated through which HF can subsequently attack the sacrificial oxide layer. The etch time determines the dimensions of the membrane. One transducer consists of a matrix of individual elements with a spacing of 25, 50 or 100 μm.

The theoretical model accounts for both the static and dynamic behavior of the device. The static analysis allows an understanding of the operating point about which the dynamic analysis applies. Because the electrostatic attraction force varies as the square of the electrode separation, while the restoring force varies approximately linearly, certain voltages and separations lead to membrane collapse. Furthermore, the behavior is hysteretic; after collapse, the membrane requires a fairly low voltage condition to snap back. The static analysis begins with the general plate equation[9]:

$$\frac{(Y_0 + A\sigma)t_m^3}{12(1-\upsilon^2)}\nabla^4 x - \sigma t_m \nabla^2 x - P_E(r) = 0 \quad (1)$$

where Y_0 is Young's modulus, A is area, σ is residual stress, t_m is the membrane thickness, υ is Poisson's ratio, x is membrane displacement, and $P_E(r)$ is the

$$Z_m = \frac{P_{uniform}}{v_{average}} = \frac{-i\omega\rho t_m ka J_0(ka)}{\left[2J_1(ka) - kaJ_0(ka)\right]} A \quad (7)$$

Equation (7) can be used to derive a two-port model[9]. Computer simulations using the two-port model match the experimental results of transmission, in air, at 11.4 MHz, 9.2 MHz, and 3.1 MHz (Figure 5).

The transmission experiments necessitated the development of transducer packaging, a custom 6 degrees of freedom tilt stage, and custom detection circuitry. The custom detection circuitry consists of a transconductance amplifier system used to detect the currents generated by the transducer. A first order analysis yields:

$$I = d\frac{(CV)}{dt}$$

which, in phasor form with constant voltage, becomes:

$$I = \omega VC$$

For our circuit, the noise floor is $2pA/\sqrt{Hz}$ as per a circuit simulator, thus, for a 10 MHz transducer with a hypothetical 2 MHz bandwidth operating at a 60 V bias, the noise floor corresponds to a capacitance of 7.5×10^{-19} F. Thus, a 100 pF transducer with a 1µm gap can detect displacements on the order of 10^{-3} Å with a 20 dB signal to noise ratio. If the gap is made thinner, the displacement sensitivity goes up proportionally, to possibly 10^{-5} Å or better. Furthermore, affording a 100 dB signal loss would require emitter displacement on the order of 100 Å. Computer simulations using the two-port model derived from the theory above indicate that such displacements would require a 6 V AC signal riding on 60 V DC. It is thus clear that these transducers are capable of high power excitation and high sensitivity detection, enabling many applications requiring a large dynamic range.

REFERENCES

1. L. C. Lynnworth, IEEE Trans. Son. Ultrason. SU **12,** 37 (1965).

2. S. Schiller, C. K. Hsieh, C. H. Chou, and B.T. Khuri-Yakub, Rev. Prog. Quant. NonDestr. Eval. **9**, 795 (1990).

3. M. I. Haller and B.T. Khuri-Yakub, Proc. IEEE Ultrason. Symp. 937 (1992)

4. C. Edwards and S. B. Palmer, IEEE Trans. on Mag. **26**, 2080 (1990).

5. G. M. Sessler, Sensors and Actuators A (Physical) **A26**, 323 (1991).

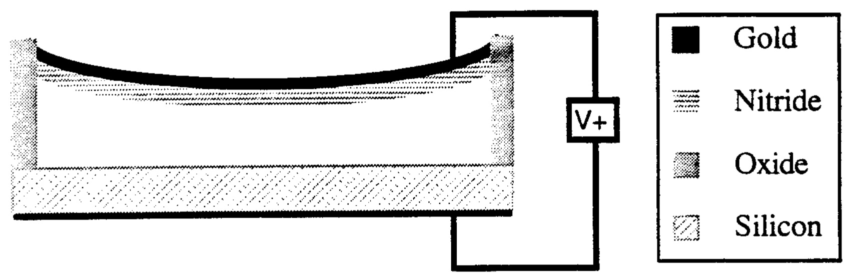
6. W. Kuhnel and G. Hess, Sensors and Actuators A (Physical) **A32**, 560 (1992).

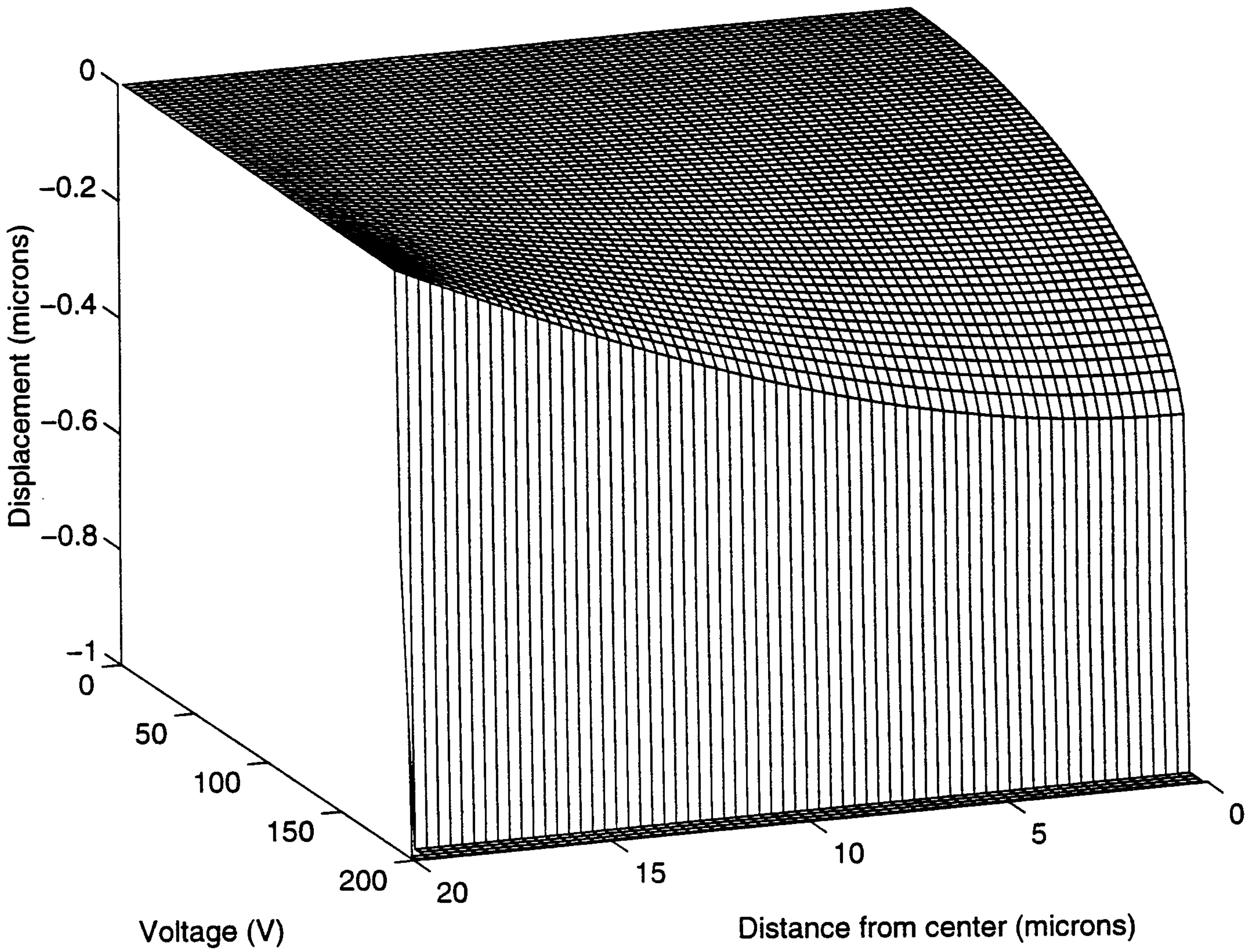
7. D. W. Schindel, D. A. Hutchins, IEEE Trans. Ultrason., Ferroelect., Freq. Cont. **42**, 42 (1995).

8. M.I. Haller, *Micromachined Ultrasonic Devices and Materials*, Doctorate Thesis, (Stanford University, 1994).

9. W. P. Mason, *Electromechanical Transducers and Wave Filters* (Van Nostrand, New York, 1942).

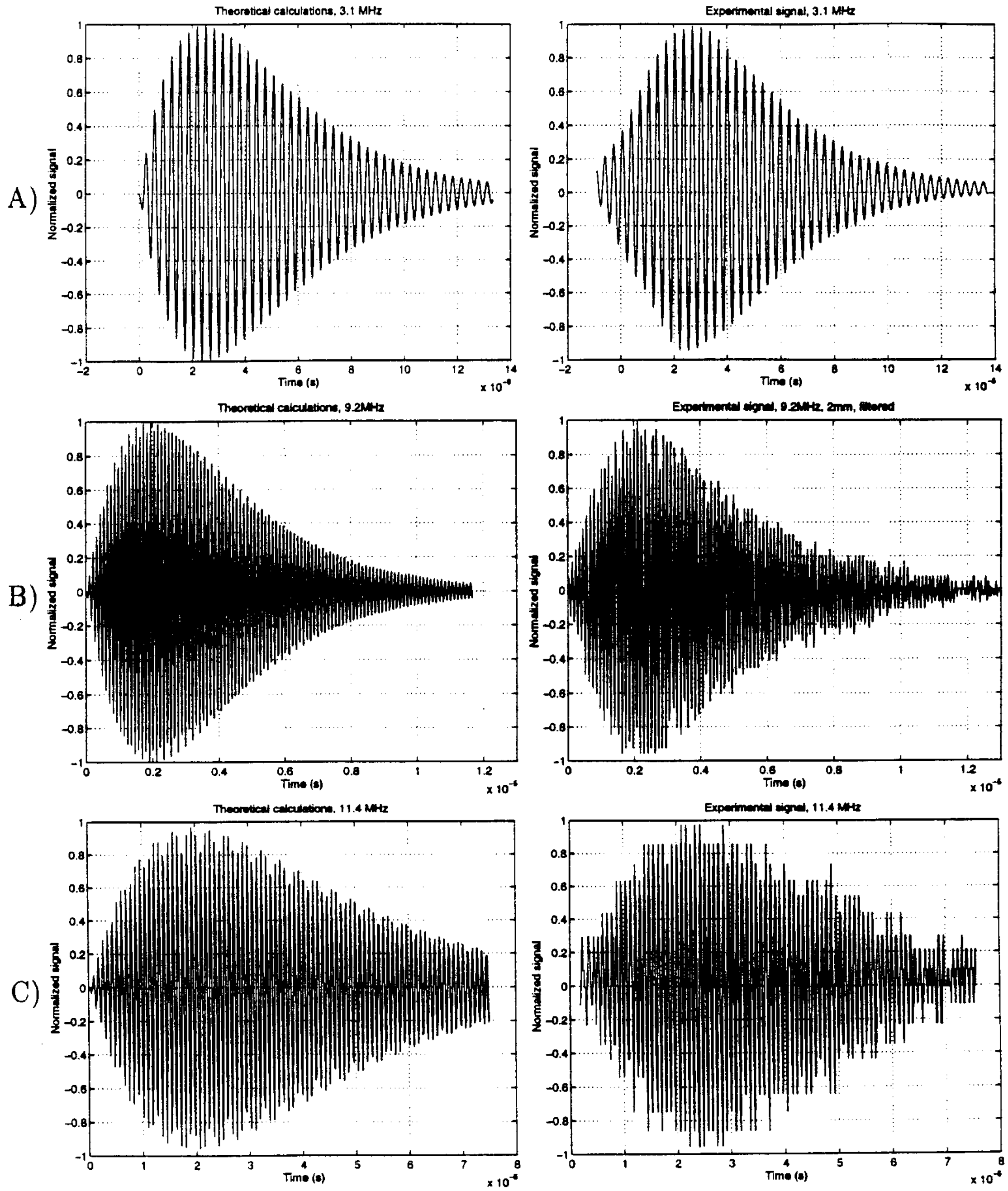
Figure 1





Displacement (microns)
0
-0.2
-0.4
-0.6
-0.8
-1
Voltage (V)
0
50
100
150
200
Distance from center (microns)
20
15
10
5
0

Fig. 5



A)
Theoretical calculations, 3.1 MHz
Experimental signal, 3.1 MHz
B)
Theoretical calculations, 9.2MHz
Experimental signal, 9.2MHz, 2mm, filtered
C)
Theoretical calculations, 11.4 MHz
Experimental signal, 11.4 MHz
Normalized signal
Time (s)